Determining the corticospinal responses to single bouts of skill and strength training

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Abstract

Neuroplastic changes in the primary motor cortex accompany performance improvements following motor practice. Recent evidence suggests that the corticospinal responses to strength and skill training are similar, following both a single session and repeated bouts of training, promoting discussion that strength training is a form of motor learning. However, these findings are limited by the lack of a light-load strength training group. Therefore, the aim of the current study was to determine whether a single-session of heavy-load strength training, light-load strength training or skill training differentially modulates the corticospinal pathway. Transcranial magnetic stimulation was used to assess the excitatory and inhibitory circuitry of the motor cortex following a single-session of skill training, and following a single-session of light-load and heavy-load strength training. Following a single-session of training, participants in all groups experienced comparable increases in corticospinal excitability (ranging from 38%-46%, all *P=<0.05*), however disparity was observed in the inhibitory responses. Corticospinal inhibition was reduced in all three single-sessions, although to a greater magnitude in the heavy-load and skill training sessions (22% and 18% respectively, compared to 11% following light-load training. All *P=<0.05*). Short-interval intracortical inhibition was reduced immediately following single-sessions of heavy-load strength training (40% *P=<0.05*) and skill training (47% *P=<0.05*), but remained unchanged following light-the load strength training session. It appears that the corticospinal responses to single-sessions of different types of strength and skill training are task-dependant. These findings reinforce the notion that strength training, at least when heavily-loaded, can be considered a form of motor learning, potentially due to the sensory-feedback involved.

Key words: Corticospinal excitability, corticospinal silent period, intracortical inhibition; neuroplasticity, skill training; strength exercise.

Introduction

There is empirical evidence that shows that neuroplastic changes in the primary motor cortex (M1) play a critical role in the acquisition of motor skills (19). The ability of the primary motor cortex to change in response to environmental stimuli has been associated with both anatomical and physiological changes following skill acquisition (24). In humans, the use of neuroimaging techniques and transcranial magnetic stimulation (TMS) measurements have comprehensively shown that motor skill training provokes changes in the cortical representation of the trained muscles in the form of increased corticospinal excitability (18). Interestingly, nonskilled or passive motor training tasks elicit no changes in the excitability of cortical movement muscle representations (29). Specifically, movement repetition in the absence of skill acquisition may be inadequate to induce changes in corticospinal excitability (19). Therefore, at a minimum, learning seems to be a necessary step for driving neuroplastic changes in the M1.

Recently, it has been suggested that strength training is a form of motor learning and thus should be associated with changes in the excitability of the trained muscles cortical representation (18). However, very little is known about the neuronal mechanisms that could be involved in neural drive during the early stages of strength training. One mechanism that has been proposed is a change in the excitability of the micro-circuitry of the primary motor cortex (15). For example, it could be hypothesised that strength training is a type of motor training that involves learning and thus there should be neuroplastic changes in cortical muscle representations that occur as a result of strength training (15). Further, because athletes are required to learn the movement pattern, i.e. activate agonist/antagonist muscles appropriately (20), it is reasonable to suggest that strength training is a form of motor learning. However, the type of strength training may be important in comparing the two forms of training, with factors such as pacing (18) and training load potentially dictating the corticospinal responses. Preliminary evidence for the role of training load comes from cross-education literature, whereby ipsilateral cortical responses are proportional to force production, with greater contraction force producing greater effect on the ipsilateral primary motor cortex (4).

In recent years, there have been attempts to identify the potential mechanisms through which motor learning and strength training may be similar. Leung and colleagues [1] showed that the elbow flexor cortical representation increased its excitability and reduced its inhibitory projections following both single sessions of visuomotor skill training and heavy-load strength training. Interestingly there were no differences between heavy-load strength training and skill training in the responses to TMS, suggesting that skill and strength training share similar neuroplastic responses. In addition, Leung and colleagues [3] further identified that the corticospinal responses to skill and strength training over a 4-wk training period were also similar, indicating that strength training is a type of motor learning because the longer-term TMS responses were not different to skill training. However, a limitation to the studies conducted to date is that skill training has typically been performed with little or no external load and strength training has been performed with relatively high loads. Thus, it remains unclear whether the corticospinal responses following a single session of light-load and heavy-load strength training are different or the same. If the responses are in fact the same, then we can conclude that strength training is a type of motor training. Since the hypothesis that strength training and skilled motor tasks share common neuroplastic responses has been raised but remains untested with low training loads, the purpose of the current study was to determine whether a single session of light-load or heavy-load strength training differentially modulates the human corticospinal pathway.

Methods

Experimental Approach to the Problem

Prior to beginning the study, subjects underwent a familiarization session that involved: (i) anthropometric measurements of height and weight (ii) strength testing to evaluate maximal voluntary dynamic elbow flexor muscle strength (1-RM),(iii) maximal voluntary isometric strength testing (MVIC) of the elbow flexor muscle and (iv) exposure to transcranial magnetic stimulation, surface electromyography and peripheral nerve stimulation. Following this visit, in a randomized-control design, participants attended the laboratory once, which was separated by 7 days from the familiarization session. A purpose made Excel macro was used to randomize subjects to the training sessions and was designed to match the training sessions to include equal numbers of males and females. Subjects were randomized (based upon gender) into four training session groups (control n = 10; heavy-load strength training n = 10; light-load strength training n = 10 and skill training n = 10) (see Figure 1). Dynamic and isometric muscle strength of the biceps brachii of the participants dominant limb for each participant was measured and determined by completing a one repetition maximum (1-RM) strength test which was collected during familiarization. The dynamic strength test data was used to determine the training load for participants allocated to either the light-load or heavy-load strength training session, while the MVIC data was used to control pre-stimulus surface electromyography during TMS testing.

Subjects

40 participants (20 male, 20 female, age: 25.9 ± 6.4 years, height: 172.4 ± 3.17, weight: 71.5 ± 4.29) were selected on a voluntary basis. All volunteers provided written informed consent prior to participation in the study, which was approved by the Monash University Human Research Ethics Committee (project number: 11882) in accordance with the standards by the Declaration of Helsinki. All subjects provided written informed consent prior to participation in the study and were informed of the benefits and risks of the investigation prior to signing the approved informed consent document to participate in the study. All subjects were right hand dominant, had not participated in strength training for a minimum of 12 months and were free from any peripheral or neurological impairment. Overall, subjects had little or no history of resistance training. Only 4 of the 40 participants reported that they had been completing strength training of the elbow flexors >1 day per week in the months prior to data collection. Consequently, they were randomly allocated to either the control or the skill-training group. All participants completed the adult safety-screening questionnaire to determine their suitability for TMS (14) and were excluded if there was a family history of epilepsy, were taking any neuroactive drugs, or had undergone neurosurgery. Where possible, factors known to confound TMS responses, subjects were instructed to avoid caffeine, medications, and exercise on the day of testing. The two visits to the laboratory were at the same time of day.

Procedures

Voluntary strength testing

Subjects in all groups performed a standard unilateral 1-RM test for the right biceps brachii, which was completed prior to the single session of strength or skill training. Following previous work [3], participants were asked what they believed that their 1-RM elbow flexion strength was and this load served as their initial starting weight. Participants performed the 1-RM test standing, holding a weighted dumbbell with one hand, with their elbow in full extension, forearm supinated, and the opposite arm placed behind their back while standing against a wall to prevent extraneous body movement. Participants were then asked to flex their arm and lift the dumbbell as if performing a standard Biceps curl. If the trial was successful, the weight of the dumbbell was increased accordingly (0.5 kg increments) on each trial following a 3-min recovery to minimise the development of muscular fatigue (16). This procedure continued until the subject could no longer complete one repetition and their prior successful trial served as their 1-RM isotonic biceps brachii strength (16). Participants completed on average three trials to achieve their 1-RM strength. The maximum weight lifted, was then used to calculate the training intensity for light-load strength training (20% 1-RM) and heavy-load strength training (80% 1-RM).

In addition, in order to quantify the appropriate level of muscle activity during TMS testing, participants completed a maximal voluntary isometric contraction (MVIC) of the dominant biceps brachii. Participants stood in the anatomical position, with the hand supinated and maintaining 90 degrees of elbow flexion. The researcher placed an adjustable weighted dumbbell in the palm of their hand. Participants were instructed to grasp the dumbbell and maintain 90 degrees of elbow flexion for 3 s, without movement of the abdomen or altering their posture. The maximal load that could be held static with correct technique served as their MVIC. Maximal root mean squared electromyography (rmsEMG) for the bicep brachii was obtained during the 3 s hold of their MVIC.

Skill Testing

Motor skill performance of the biceps brachii was determined by calculating the sum of errors during an elbow-flexion visuomotor tracking task according to the procedures by Leung et al., [1, 3]. Briefly, participants stood with their back straight against the wall with their forearm supinated in order to replicate the position that was used during the strength-training protocol. Participants performed three sets of 10 s of visuomotor tracking on a purpose built computer program (Jgcode V2.0, Australia). Each 10 s of visuomotor tracking had a range of motion from 30° to 140°elbow flexion-extension, and the animated arm moved at 0.2 Hz, 0.8 Hz and 1.3 Hz, respectively. The visuomotor tracking task required each participant to move their arm in response to the movement patterns of an animated arm displayed on a computer screen. The position and movement of the elbow joint was tracked by a wireless electromagnetic goniometer (ADInstrumennts, Bella Vista, Australia). Participants were provided with a percentage score of time spent in the correct tracking position while performing the tracking task.

Strength training session protocol

Participants allocated to the strength training session groups performed supervised unilateral elbow flexion/extension exercise (i.e., a standard series of dumbbell bicep curls) to a repetition timing monitored by a metronome (2 s concentric; 4 s eccentric) (16). For the heavy-load strength training session, participants completed four sets (6–8 repetitions; 80% 1-RM) with 2.5 min rest between sets. For the light-load strength training session, participants completed four sets of 20 repetitions (20% 1-RM) with 30 s rest between sets. The total time to complete the heavy-load strength training session was 9 min and 6.5 min following the light-load strength training session. On average, the total work performed for the heavy-load strength training session group was 28, while the light-load strength training session group completed 80 repetitions during the intervention.

Skill training session

For the skill training session group, participants performed four sets of 56 s of visuomotor tracking on a custom-built computer program (Jgcode V2.0, Australia). The position and movement of the elbow joint was tracked by a wireless electromagnetic goniometer (ADInstruments, Bella Vista, Australia). During visuomotor tracking, participants observed two animated arms, one automated and the other controlled by the participant to track the movement of the automated arm. Participants were provided with a report of a percentage score of time spent in the correct position while performing the tracking task. The visuomotor tracking task has been previously reported [1, 3]. The tracking task had a range of motion from 30° to 140° and the animated arm moved within a 0.2–1.3 Hz range. This position was similar to the strength training session, and only elbow flexion and extension movements were permitted (similar to a biceps curl). The difficulty of the tracking task was adjusted by randomising the speed of the task throughout the training block. Specifically, participants performed four sets of the visuomotor tracking task by synchronizing the dominant arm to a computer-controlled arm that moved through 120° range of motion timed to a pseudo-random frequency selected from a range between 0.2 Hz and 1.3 Hz. The tracking task was also matched to the duration of the strength training task and each set consisted of 56 s of visuomotor tracking. A 2.5 min recovery period separated each set.

Control condition:

The control group reported to the laboratory under the same conditions as the experimental strength training and skill training session groups and completed the exact same testing procedures; however, they did not complete any intervention, rather they sat quietly in the laboratory for the same duration as it took to complete the heavy-load strength-training session. Following this, they received the same post-testing measurements as the experimental groups.

Transcranial magnetic stimulation and surface electromyography

TMS was applied over the left primary motor cortex using a BiStim unit attached to two Magstim 200^2 stimulators (Magstim Co, Dyfed, UK) to produce motor-evoked potentials recorded from the right biceps brachii. A figure-eight coil, with an external loop diameter of 9 cm, was held over the left primary motor cortex at the optimum scalp position to elicit motor-evoked potentials in the right biceps brachii. The induced current flowed in a posterior-to-anterior direction. Sites near the estimated center of the biceps brachii were first explored to determine the 'optimal site' at which the largest motor-evoked potential amplitude could be evoked, and active motor threshold was established as the stimulus intensity at which at least five of ten stimuli produced motor-evoked potential amplitudes of greater than 200 µV [3]. Following all conditions (i.e. skill and strength training), active motor threshold was retested and adjusted if required. In order to ensure that all TMS stimuli were delivered consistently throughout pre and post-testing, participants wore a fitted cap that was marked with a latitude-longitude matrix, positioned and referenced to the nasion-inion and interaural lines. All TMS stimuli were delivered during low-level isometric contraction of the biceps brachii (5±1% of maximal root-mean squared electromyography [rmsEMG]), which required the participants to maintain an elbow joint angle of 90° elbow flexion. Joint angle was measured with an electromagnetic goniometer (ADInstruments, Bella Vista, Australia), with visual feedback provided on a screen visible to both the participant and the researcher. Holding the lower arm in this joint position equated to 5 ± 1% rmsEMG maximum. Because this position resulted in a low level of muscle activity, and to ensure that background muscle activity was consistent between TMS stimuli, rmsEMG were recorded 100 ms before the delivery of each TMS pulse. During the TMS trials, visual feedback was presented to the volunteer to display an upper limit of 5% rmsEMG; participants were instructed to maintain their muscle activation levels below this upper limit. The stimulus delivery software (LabChart 8 software, ADInstruments, Bella Vista, NSW, Australia) was set, so that stimuli were not delivered if the rmsEMG, 100 ms immediately prior to the stimulus, exceeded 5 ± 1% (see Table 1). Single-pulse TMS was used to assess corticospinal excitability and inhibition (silent period duration), while paired-pulsed TMS assessed short-interval cortical inhibition pre and post the training sessions. The single-pulse TMS protocol comprised of 20 stimuli elicited at a stimulus intensity of 130% active motor threshold, and the peak-to-peak amplitude was analysed. This was then followed by 20 paired-stimuli comprised of a subthreshold conditioning stimulus at 70% active motor threshold, followed by a suprathreshold test stimulus at 130% active motor threshold, with an interstimulus interval of 3 ms. For both single-pulse and paired-pulse TMS, the 40 stimuli were delivered in random order every 6-12 s to avoid stimulus anticipation, and 1 min rest was provided between the single-and paired-pulse phases to reduce muscle fatigue.

Maximal compound muscle action potential

Direct muscle responses were obtained from the trained biceps brachii muscle by supramaximal electrical stimulation (pulse width 200 µs) of the Brachial plexus (Erbs point) during light background muscle activity (DS7A, Digitimer, UK). An increase in current strength was applied to Erbs point until there was no further increase observed in the amplitude of the EMG response (M-wave). To ensure maximal responses, the current was increased an additional 20% and the average M-wave was obtained from five stimuli, with a period of 6-9 s separating each stimulus. M_{MAX} was recorded at baseline and following the interventions, to ensure that there were no changes in peripheral muscle excitability that could influence motor-evoked potential amplitude.

Data analysis

Pre-stimulus rmsEMG activity was determined in the biceps brachii muscle 100 ms before each TMS stimulus during pre- and post-testing. Any trial in which pre-stimulus rmsEMG was greater than 5 ± 1% of maximal rmsEMG was discarded and the trial was repeated. The peak-to-peak amplitude of motor-evoked potentials were measured in the right biceps brachii muscle contralateral to the cortex being stimulated in the period 10–50 ms after stimulation. Motor-evoked potential amplitudes were analyzed (LabChart 8 software; AD Instruments) after each stimulus was automatically flagged with a cursor, providing peak-to-peak values in mV, averaged and normalized to the M-wave, and multiplied by 100. Corticospinal silent period durations were determined by examining the duration between the onset of the motor-evoked potential and the resolution of background surface electromyography, which was visually inspected and manually cursored, with the experimenter blinded to each condition. The average from 10 stimuli was used to determine corticospinal silent period duration. Short-interval cortical inhibition was expressed as a percentage of the unconditioned single-pulse motor-evoked potential amplitude.

Sample size and Statistical analysis

The target sample size of 40 was based on a priori calculation, which included the observed effect size from our previous experiment [1]. In previous experiments, samples sizes of ~10 have been adequate to observe statistically significant changes in motor-evoked potentials and short-interval cortical inhibition after a single session of skill and strength training [1].

All data were first screened to ensure they were normally distributed. To have sufficient data to test for questions of normality, all data from baseline motor-evoked potentials, short-interval cortical inhibition and corticospinal silent period trials were used to establish the distributional properties. No variable's z-score of skew or kurtosis was excessive. Further, the Shapiro-Wilk test suggested that the variable motor-evoked potential amplitude for the skill training group was non-normal (W=0.791; P = 0.01) and corticospinal silent period duration for the control group (W=0.791; P = 0.01). However, these violations appeared to only be mild from examination of frequency histograms and detrended Q-Q plots, and was not considered sufficient to warrant a more conservative analytical strategy, thus it was decided to treat the data as essentially normally distributed. A one-way ANOVA was conducted on all baseline values, which included corticospinal excitability (motor-evoked potential expressed as percentage of M-wave), short-interval cortical inhibition (expressed as a percentage of the test response) and corticospinal silent period duration (in milliseconds) to ensure that there were no differences between groups. A 2-way repeated measures ANOVA (Factors: Two time points and Four Training Session Groups) assessed changes in biceps brachii rmsEMG, motor-evoked potential amplitude, corticospinal silent period duration, short-interval cortical inhibition and M-wave. If significant main effects were found, univariate and post hoc analysis (Tukey's multiple comparisons test) was used to analyse the percentage change comparing the training sessions (control, skill-training, light-load strength training and heavy-load strength training). For all comparisons, effect sizes of 0.2, 0.5, and 0.8 were established to indicate small, moderate and large comparative effects (Cohen's d). The level of significance was set at $P < 0.05$. SPSS version 22.0 (SPSS Inc., Chicago, IL) and was used for all statistical analyses, and all results are displayed as mean ± SE and 95% confidence intervals (CI) unless stated otherwise.

Results

Baseline electrophysiological and strength measures

Table 1 displays the raw data for the percentage of stimulator output for active motor threshold, rmsEMG for single and paired-pulse TMS, while Table 2 displays the raw data for motor-evoked potential amplitude, short-interval cortical inhibition and corticospinal silent period. At baseline, there were no significant differences across groups for motor-evoked potential amplitude ($F_{3,\ 36}$ = 0.157; P = 0.924), short-interval cortical inhibition ($F_{3,\ 36}$ = 1.16; P = 0.339), corticospinal silent period ($F_{3,\ 36}$ = 0.157; P = 0.924), SICI ($F_{3,\ 36}$ = 1.04; P = 0.384) or for active motor threshold ($F_{3,\ 36}$ = 1.65; P = 0.173). There were also no differences in pre-stimulus rmsEMG across groups at baseline ($F_{3,\ 36}$ = 0.368; P = 0.776) or M_{MAX} ($F_{3,\ 36}$ = 0.3004; P = 0.948). In a similar pattern, there were no differences in baseline 1-RM strength across the groups ($F_{3,\ 36}$ = 2.63; P = 0.09; control: 14.7 ± 1.2 kg; heavy-load strength training: 17.6 ± 2.9 kg; light-load strength training: 15.8 ± 1.6 kg and skill training: 14.1 ± 3.1 kg). Further, there were no differences in MVIC strength across groups ($F_{3,\ 36}$ = 1.37; P = 0.634; control: 182.5 ± 12.5 N; heavy-load strength training: 178.2 ± 16.1 N; light-load strength training: 173.7 ± 14.8 N and skill training: 180.3 ± 17.1 N).

Insert table 1 here

Pre-stimulus EMGs

Following the training sessions, there was no TIME ($F_{1,\ 36}$ = 2.99; P < 0.092) or GROUP X TIME interactions ($F_{3,\ 36}$ = 0.355; P = 0.785) for pre-stimulus rmsEMG. In a similar manner, there were no TIME ($F_{1,\ 36}$ = 0.11; P < 0.740) or GROUP X TIME interactions ($F_{3,\ 36}$ = 1.3; P = 0.290) for active motor threshold or M_{MAX} ($F_{3,\ 36}$ = 0.066; P = 0.977).

Changes in corticospinal excitability

Motor-evoked potential amplitudes were obtained at baseline and immediately post a single training session (see Fig. 2; Table 2). Following the three training sessions there was a main effect for TIME ($F_{1,\ 36}$ = 58.7; P < 0.0001) and a GROUP X TIME interaction ($F_{3,\ 36}$ = 11.3; P < 0.0001). Immediately following the skill and strength training sessions, the increase in motor-evoked potential amplitude was significantly greater following skill training (38% ± 11%, 95% CI 30.93 to 46.42, d = 2.96), light-load strength training (46% ± 11.28%, 95% CI 37.55 to 53.70, d = 3.47) and heavy-load strength training sessions (37% ± 10.68%, 95% CI 29.29 to 44.58, d = 3.47) compared to the control session (3.72% ± 11.8%, 95% CI -4.27 to 12.18). There were no significant difference in motor-evoked potential amplitudes between skill-training, light-load strength training or heavy-load strength training sessions (all P > 0.05).

Insert Figure 2 here

Changes in corticospinal inhibition

The duration of the corticospinal silent period was obtained at baseline and immediately post the training sessions (see Fig. 3; Table 2). Following the three training sessions there was a main effect for TIME ($F_{1, 36}$ = 262; $P < 0.0001$) and a GROUP X TIME interaction ($F_{3, 36}$ = 31; $P < 0.0001$). Immediately following the skill and strength training sessions, the decrease in corticospinal silent period was significantly greater following skill training (18% ± 3.5%, 95% CI 16.01 to 20.94, d = 6.36), light-load strength training (11% ± 6.1%, 95% CI 6.49 to 15.23, d = 2.24) and heavy-load strength training sessions (22% ± 5%, 95% CI 18.54 to 25.59, d = 5.64) compared to the control session (1.36% ± 1%, 95% CI 0.64 to 2.09). Further, the magnitude of change following both skill training (P = 0.002, d=1.62) and heavy-load strength training sessions ($P < 0.0001$, d=2.08) was greater when compared to the light-load strength training session. There was no difference between skill training and heavy-load strength training sessions (P = 0.273).

Insert figure 3 here

Changes in short-interval cortical inhibition

Short-interval cortical inhibition was obtained at baseline and immediately post the training sessions (see Fig. 4; Table 2). Following the three training sessions there was a main effect for TIME ($F_{1, 36}$ = 22.5; $P < 0.0001$) and a GROUP X TIME interaction ($F_{3, 36}$ = 8.14; P = 0.0003). Immediately following skill and heavy-load strength training sessions, the reduction in short-interval cortical inhibition was significantly greater following skill training (47% ± 40%, 95% CI 17.6 to 75.9, d = 1.56), and heavy-load strength training sessions (40% ± 28%, 95% CI 20.1 to 60.4, d = 1.92) compared to the light-load strength training session (4% ± 19%, 95% CI -9.41 to 18.2, d = 0.33) and the control group (3.72% ± 11.8%, 95% CI -4.46 to 3.59). There was no difference in the magnitude of short-interval cortical inhibition release between skill-training and the heavy-load strength training session (P = 0.947).

Insert figure 4 here

Insert table 2 around here

Discussion

The aim of the current study was to investigate whether a single session of light-load strength training and heavy-load strength training differentially modulates the corticospinal pathway when compared with skill training. The main findings of the study showed that all three types of training sessions increased corticospinal excitability, with no difference in the magnitude of change observed between training session groups. Similarly, there were significant reductions in corticospinal silent period following all three types of training sessions. However, while the light-load strength training session group did experience a reduction in corticospinal silent period, the change was less than the heavy-load strength training and skill training session groups, which produced parallel reductions. While a single session of both skill training and heavy-load strength training reduced short-interval cortical inhibition to a comparable extent, there were no changes in short-interval cortical inhibition following the light-load strength training session. These data demonstrate that while heavy-load strength training and skill training share similar corticospinal responses following a single session of training, the inhibitory responses to strength training are specific to the parameters of the task, which may include factors such as the sensory demands.

A major finding of this study was that both the light-load strength training and heavy-load strength training sessions produced similar increases in corticospinal excitability, which are comparable with those observed following skill training. This common increase shared between all training session groups is consistent with the existing literature, including a recent systematic review that concluded that heavy-load strength training and light-load strength training both acutely increase corticospinal excitability (20). This finding is unequivocal across a range of contraction types (17, 23), as well as muscles trained ((17, 19, 23). Skill training is also well reported to induce acute increases in corticospinal excitability in the period immediately post training (12), including visuomotor tracking tasks similar to those used in this study (19). Although there is some debate regarding whether corticospinal excitability increases or decreases following motor training, it is generally accepted, that a shift in corticospinal excitability in either direction following a single session of training is a shared property between most forms of focused motor practice (32). Importantly, this extends to relatively uncomplicated tasks, including ballistic digit practice [12], indicating that task complexity may not be an important factor in inducing changes in corticospinal excitability. It is therefore likely that light-load strength training is also a sufficient stimulus to induce increases in corticospinal excitability. This is in contrast to early findings, which observed that repetition in the absence of acquiring a skill is insufficient to induce changes in corticospinal excitability (29). While the origin of the changes underpinning the increase in corticospinal excitability in the current study is not clear, it has been reported that following both heavy-load strength training (23) and visuomotor tracking (27), spinal excitability is also increased (9), which may indicate that changes in corticospinal excitability are at least in part due to increased spinal excitability.

The notion that both light-load strength training and heavy-load strength training share similar increases in corticospinal excitability following a single session of training which are akin to those following skill training, raises the question of the functional purpose of such an increase. It could simply be that an increase in corticospinal excitability following strength training is an attempt by the central nervous system to diminish or circumvent any muscular fatigue developed throughout the training intervention (17). For example, lactate accumulated during light-load training has the potential to increase corticospinal excitability (2). However, whether or not light-load strength training is always sufficient to induce substantial muscular fatigue and subsequent increases in corticospinal excitability is disputable. This may therefore, indicate that an increase in corticospinal excitability following strength training could serve additional purposes. For example, it has been suggested that increases in corticospinal excitability relate to processes of actively acquiring and consolidating a task rather than mere activation of a muscle (28), and that early consolidation of a task commences in the primary motor cortex from the first exposure to a task (13). Therefore, the acute increases in corticospinal excitability following a single session of different types of motor training may be an early marker of neuroplasticity related to the early phase of skill learning. This supports the view that strength training, potentially regardless of load, could be considered a form of skill training.

The transient increase in corticospinal excitability potentially depends on a release of inhibitory synaptic activity in the micro-circuitry of the primary motor cortex (6), as well as spinal influences (23). Further, it is entirely plausible that light-load strength training and heavy-load strength training produce increases in corticospinal excitability through separate and independent mechanisms. The increase in corticospinal excitability following light-load strength training may be contingent on the accumulation of metabolites, while increases following heavy-load strength training may be more reliant on factors such as increased sensory feedback, which may increase neural drive to the motorneuron pool.

This study provides evidence that heavy-load strength training and skill training share comparable responses, while light-load strength training produces a unique inhibitory response following a single bout of training. While light-load strength training significantly decreased the corticospinal silent period, it did not do so to the same magnitude as heavy-load strength training and skill training which shared parallel responses. Intracortical inhibition, as assessed by the corticospinal silent period, remained unchanged by light-load strength training, whereas both heavy-load strength training and skill training produced comparable reductions following training.

Although there is some evidence that relatively lighter training loads can produce the same magnitude of reduction in corticospinal inhibition as heavier training loads following a single session of training (17), these findings were not replicated in this study. This disparity is likely due to the training loads employed, with Latella and colleagues using a 12RM scheme at approximately 67% of 1RM, whereas the current study used 20% of 1RM. The reduction in cSP in response to heavy-load strength training supports existing evidence (17, 20). However, the observed reduction following skill training adds to the inconsistent findings regarding corticospinal inhibitory responses to motor training. For example, no differences were detected in corticospinal silent period following visuomotor tracking task (25)), but a similar follow-up study found a reduction in corticospinal silent period following both slow and fast visuomotor tracking (26). Increases in corticospinal silent period have been detected following each set during a heavy-loaded elbow flexion training session (33), which is contradictory to the current finding.

It was also observed in the present study that intracortical inhibition, indexed by short-interval cortical inhibition, was not reduced following a single bout of light-load strength training, but both heavy-load strength training and skill training led to reductions. Reductions in intracortical inhibition have been observed in tandem with increases in corticospinal excitability following motor practice, including heavy-load strength training (19) and skill training (19, 28). However, changes in short-interval cortical inhibition following motor practice remain relatively inconsistent. For example, decreases have been observed following skill training (3, 8), alongside reports of no change (32). Similarly, inconsistent reports exist following strength training, with decreases [1] and no changes (17) observed. Thus, changes in intracortical inhibition appear to be particularly sensitive to the parameters of the motor task involved; a notion which is supported by the results of this study. The separate and independent responses observed in short-interval cortical inhibition and corticospinal silent period add to previous findings that motor training has distinctly different effects on separate inhibitory-neuronal populations (17, 20, 21). Differences in inhibitory responses between training types may be due to the unique demands of each training protocol and the subsequent fatigue status of an individual (36), however, a limitation of the current study is that indices of fatigue were not measured, despite there being no changes in M_{MAX}.

The disparity in inhibitory response between the light-load strength training and heavy-load strength training sessions raises the question; what are the features of heavy-load strength training that ultimately produce a more substantial response in markers of inhibition when compared with light-load strength training? Further, what are the elements of heavy-load strength training which produce corticospinal responses akin to those observed following a session of skill training? The answers could lay in the demands of the task; particularly the sensory feedback. It is well established that sufficiently challenging the nervous system is important in maximising the neuroplastic response (7, 19). For example, as observed in the current study, externally-paced strength training stimulus generates significant increases in corticospinal excitability, as well as reductions in short-interval cortical inhibition following both a single session (19), as well as following short-term strength programmes (7), whereas self-paced strength training may be insufficient to induce substantial changes (12, 19). Visuomotor tracking that is paced with a metronome increases corticospinal excitability compared to non-paced tracking (1). These greater responses are purported to result, in part, through increased sensory feedback from contracting muscles (10, 11) and the activation of specific neural pathways relevant to the task (3, 28). However, despite external-pacing being utilised for both light-load strength training and heavy-load strength training in the current study, heavy-load strength training still generated a greater magnitude of reduction in inhibitory responses. This indicates that externally-paced training is not sufficient enough alone to maximise the acute corticospinal responses to training, and that combining pacing with increased training load is necessary to generate more substantial responses. This validates previous findings, whereby the inhibitory responses to a simple digit abduction task is unique to the level of force employed during a contraction, with short-interval cortical inhibition being reduced incrementally with increasing force production during graded contractions (38). Further, the dynamic nature of externally-paced heavy-load strength training substantially increases muscle afferent feedback (10, 11, 19), and motor tracing tasks engage the visual cortex, implying that skill training and heavy-load strength training share the trait of challenging the sensory system more so than light-load strength training. Indeed, the light-load strength training session completed training that shared many qualities parallel with the heavy-load strength training session, including external-pacing and dynamic contractions, showing the only point of difference was the force required. This may aid in explaining the unique responses.

The acute corticospinal responses following a single session of training may reflect early offline processes which are integral in the progression of acquiring and consolidating a task. Therefore, it is also necessary to consider the performance consequences of such responses and how they may differ between heavy-load strength training, light-load strength training and skill training. It has been demonstrated that both skill performance (13, 30, 38) and force generating capacity can be enhanced immediately following a single session of training. This suggests that the sites and processes of neural adaptation to skill training and heavy-load strength training maybe similar, but it is unclear how different training loads and parameters specifically influence the TMS responses. In light of this, following repeated training sessions, there are several lines of evidence that show heavy training loads yield greater gains in strength compared to light training loads (5, 22, 37), and moderate training loads (35), even when overall training volume in heavy strength training groups is less than in light strength training groups. Further, lightly loaded strength training consistently increases muscular endurance (31), whereas training with heavy loads does not (34). This, combined with the findings of the current study, provide evidence that both the corticospinal and performance responses to training are task-specific. It is conceivable that the acute, transient responses following a single session of motor training, form the basis for long-term neuroplastic changes which drive and accompany the aforementioned increases in performance, although the link between the two remains relatively unclear. Maximising the neuroplastic response to a single session, via increased training load, likely compounds from session to session, and may aid in explaining the different functional outcomes of light-load strength training and heavy-load strength training training-programmes.

Although the current study provides novel evidence suggesting that strength training with lighter loads produces a unique set of corticospinal responses, the results can only be generalised to healthy and untrained young adults, and the findings are limited to the current tasks involved. Future studies should seek to measure both the strength performance and the fatigue status of participants prior to, during and following training, in order to identify further mechanisms which may be responsible for the differential responses.

Practical Applications

The current study provides novel evidence of the corticospinal responses to a single session of skill and strength training, and identifies, the unique acute responses of strength training with a lighter load. Although a strength-training stimulus using a light load increases corticospinal excitability to the same extent as a stimulus from heavy strength training and motor skill training, it reduces corticospinal inhibition to a lesser extent and does not influence intracortical inhibition. The corticospinal responses to strength training with heavy loads are akin to those observed following motor skill training, validating previous evidence from Leung and colleagues (18, 19) and suggests that the processes and structures underlying early skill and strength acquisition during the initial weeks of training may indeed have similarities. Taken together, these findings show the capacity for the corticospinal pathway to alter its response based on the demands of the training task. Light-load strength training may be insufficiently demanding on the motor system when compared with skill and heavy strength training, leading to a diminished acute inhibitory response. This may be an early adaptation which drives greater strength improvements following heavy strength training as opposed to training with lighter weights. Further, it highlights the value of suitably challenging the motor system in order to maximise the acute corticospinal response and, potentially, the longer-term corticospinal and performance adaptations. Further research should seek to track how the corticospinal and behavioural responses to strength training may accumulate from a single session across multiple sessions, and ultimately contribute to long-lasting changes in muscular strength.

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FIGURE LEGENDS

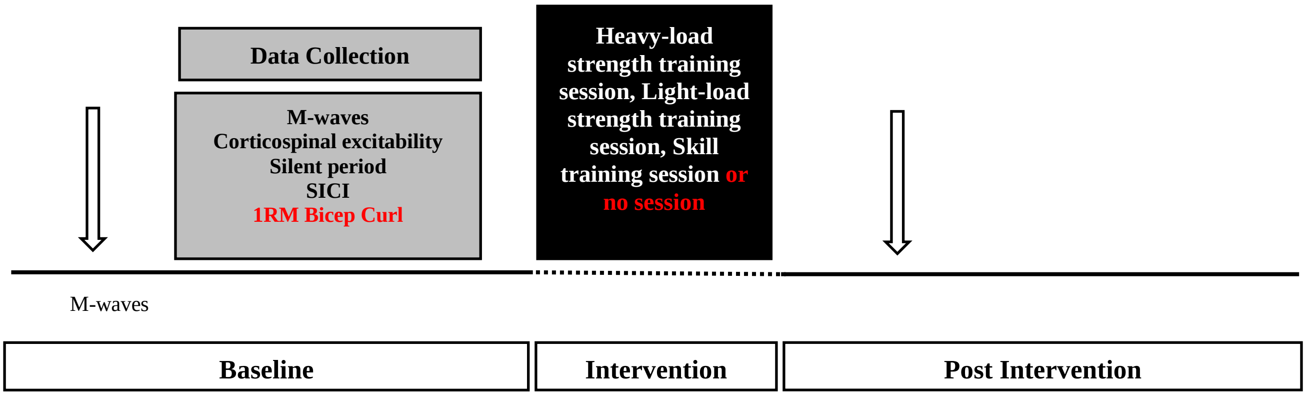

Figure 1: (A) Schematic representation of the experimental design with measures obtained prior to and following heavy-load strength training, light-load strength training and visuomotor skill training. Pre- and post-measures included assessment of peripheral muscle excitability (M_{MAX}), corticospinal excitability, corticospinal inhibition and short-interval intracortical inhibition of the trained biceps brachii muscle.

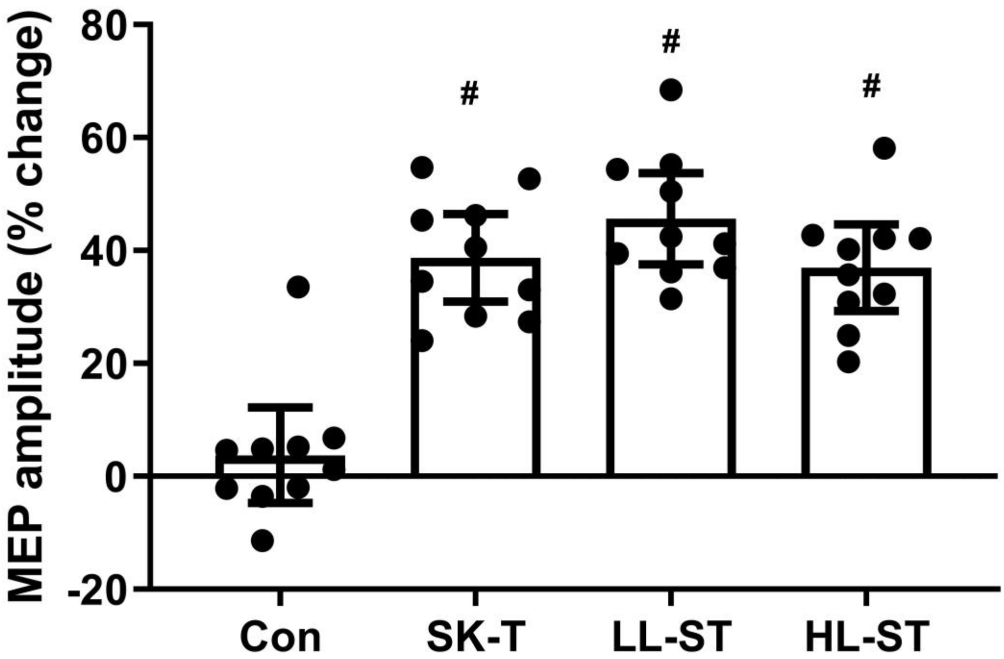

Figure 2: Change in corticospinal excitability (% increase in MEP amplitude normalised to M_{MAX}) of the trained biceps brachii (mean ± SE) following heavy-load strength training, light-load strength training and visuomotor skill training. #Denotes a significant increase in corticospinal excitability from baseline following skill –training, light-load strength training and heavy-load strength training compared to the control group (between groups effect).

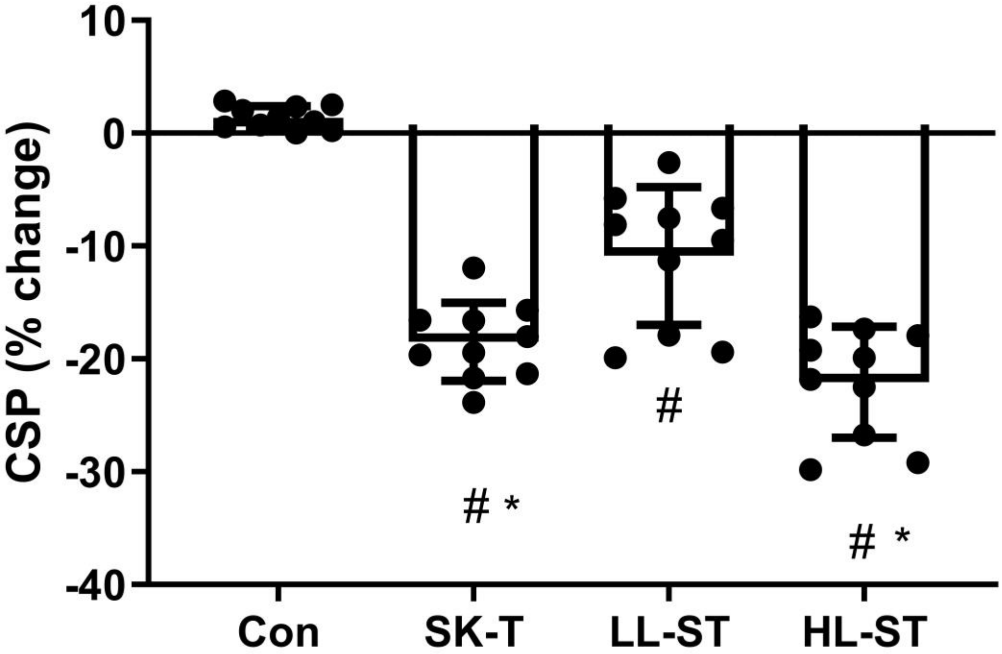

Figure 3: Change in corticospinal inhibition (% decrease in silent period duration) of the trained biceps brachii (mean ± SE) following heavy-load strength training, light-load strength training and visuomotor skill training. #Denotes a significant decrease in corticospinal inhibition from baseline following heavy-load strength training, light-load strength training and visuomotor skill training (within group effect). *Denotes a significant reduction in corticospinal inhibition following visuomotor skill training and heavy-load strength training when compared to the light-load strength training and control groups (between groups effect). cSP; corticospinal silent period.

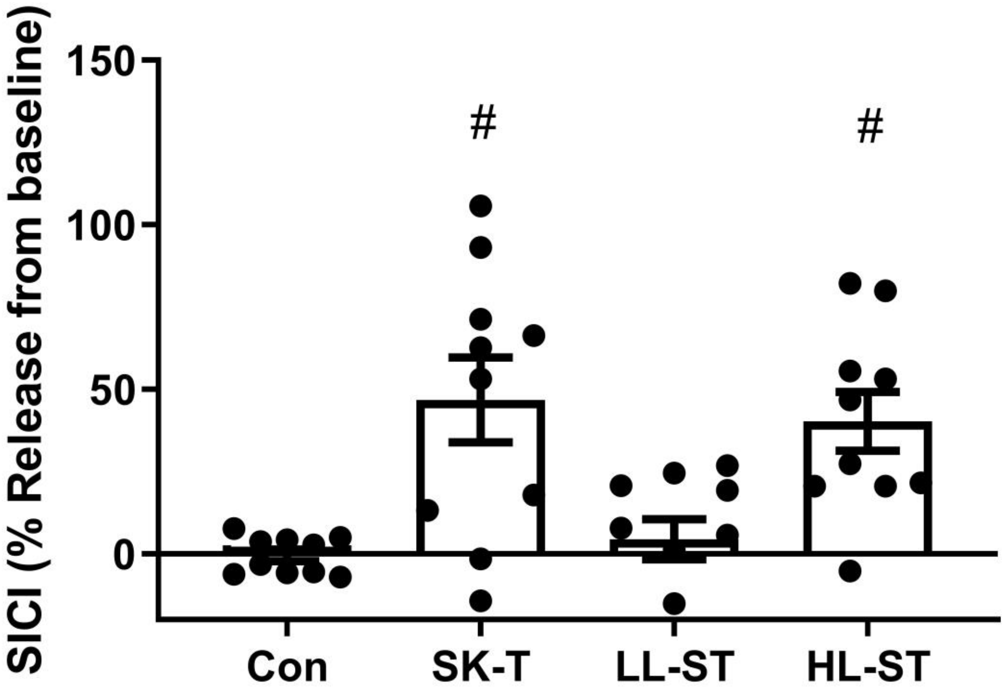

Figure 4: Change in SICI (% change) of the trained biceps brachii (mean ± SE) following heavy-load strength training, light-load strength training and visuomotor skill training. #Denotes a significant release in SICI from baseline following visuomotor skill training and heavy-load strength training compared to light-load strength training and the control group (between groups effect).

Table 1. Mean (± SD) and percentage change for AMT stimulus intensity, M_{MAX} and single- and paired--pulse TMS pre-stimulus rmsEMG prior to and following a single session of motor training for the control and training groups.

	AMT SI (%)			SP rmsEMG (% rmsEMGmax)			PP rmsEMG (% rmsEMGmax)		
	Pre	**Post**	***P* value**	**Pre**	**Post**	***P* value**	**Pre**	**Post**	***P* value**
Control Group	28.4 ± 3.57	28.3 ± 3.73	0.94	3.86 ± 0.02	3.83 ± 0.02	0.99	3.76 ± 0.02	3.75 ± 0.03	0.99
Visuomotor Skill Training	27.7 ± 5.31	27.7 ± 5.57	>0.99	4.14 0.02	4.11 0.03	0.99	4.05 ± 0.02	4.10 ± 0.02	0.93
Light Load Strength Training	30.8 ± 3.01	30.6 ± 3.16	0.57	3.81 ± 0.03	3.69 ± 0.02	0.58	3.64 ± 0.03	3.73 ± 0.02	0.65
Heavy Load Strength Training	30.6 ± 2.32	30.8 ± 2.40	0.58	3.42 ± 0.02	3.28 ± 0.03	0.49	3.3 ± 0.03	3.35 ± 0.01	0.92

AMT SI: active motor threshold stimulus intensity. Single (SP) and paired pulse (PP) rmsEMG was pooled across the 20 stimuli.

Table 2. Mean (± SD) and percentage change for MEPs, silent period and SICI for control and training groups following a single session of motor training.

	MEP amplitude (% of MMAX)			Silent Period (ms)			SICI (% of test response)		
	Pre	**Post**	***P* value**	**Pre**	**Post**	***P* value**	**Pre**	**Post**	***P* value**
Control Group	3.07 ± 1.21	3.15 ± 1.28	0.33	0.122 ± 0.01	0.121 ± 0.01	0.7631	52.47 ± 20.17	51.59 ± 17.94	0.99
Visuomotor Skill Training	2.50 ± 1.28	3.50 ± 1.29	0.001	0.135 ± 0.01	0.108 ± 0.01	<0.0001	33.69 ± 6.53	49.87 ± 6.11	<0.0001
Light Load Strength Training	7.81 ± 5.04	11.41 ± 5.28	0.001	0.129 ± 0.01	0.106 ± 0.01	<0.0001	42.06 ± 13.96	42.30 ± 14.18	>0.9999
Heavy Load Strength Training	6.80 ± 3.36	9.24 ± 3.55	0.0002	0.134 ± 0.01	0.113 ± 0.01	<0.0001	39.53 ± 10.12	55.34 ± 10.61	0.0001

MEP and Silent Period measured at 130% of AMT.